Overview of the Mars 2020 Parachute Risk Reduction Activity

Dr. Christopher L. Tanner
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
christopher.l.tanner@jpl.nasa.gov

Dr. Ian G. Clark
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
ian.g.clark@jpl.nasa.gov

Allen Chen
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
allen.chen@jpl.nasa.gov

Abstract—**In 2012, the Mars Science Laboratory (MSL) landed safely on the surface of Mars using a supersonic Disk-Gap-Band (DGB) parachute, which was structurally qualified for flight via a subsonic wind tunnel test program. Results of the Low-Density Supersonic Decelerators (LDSD) program have called into question the methodology and principles that form the foundation of the MSL subsonic test program. LDSD discovered that quasi-static subsonic proof loading a parachute via ground testing may not provide canopy stresses that sufficiently bound the stresses experienced during a rapid supersonic inflation at Mars. Additionally, deeper scrutiny of the materials and structural margins present in previously successful supersonic DGBs indicated that the MSL parachute flew with lowest margins of any previous parachute. These factors have increased the perceived risk of reusing a heritage MSL DGB parachute design with a subsonic test program for Mars 2020.**

To reduce this risk, a series of risk reduction steps were initiated starting in 2016. First, two parachute assemblies have been pursued in parallel: a Build-to-Print (BTP) MSL parachute, designed and manufactured by Pioneer Aerospace Corporation, which maintains the heritage of the successful MSL parachute, and a strengthened parachute, designed and manufactured by Airborne Systems North America, which uses higher strength materials throughout the parachute assembly but maintains the same overall size as the MSL parachute. Second, each parachute system was tested in a subsonic wind tunnel to examine the canopies in their fully inflated state and assess the workmanship of each canopy. Finally, full-scale parachutes from each vendor will experience at least one supersonic inflation at Mars-relevant Mach numbers and atmospheric densities at Earth via a supersonic sounding rocket test campaign. This paper presents high-level details regarding the risk reduction strategy, the two candidate parachute configurations, the ground test program, and the supersonic flight test program, and brief results from each of the test programs.

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1. Introduction

In August 2012, a 21.35 m nominal diameter Disk-Gap-Band (DGB) parachute successfully inflated at Mars at a Mach number of 1.70, reaching a peak inflation load of approximately 34,580 lb [1]. This parachute, shown in Figure 1, helped provide a safe landing for the Curiosity rover and marked the seventh successful use of a supersonic DGB parachute to safely land a payload on the surface of Mars.

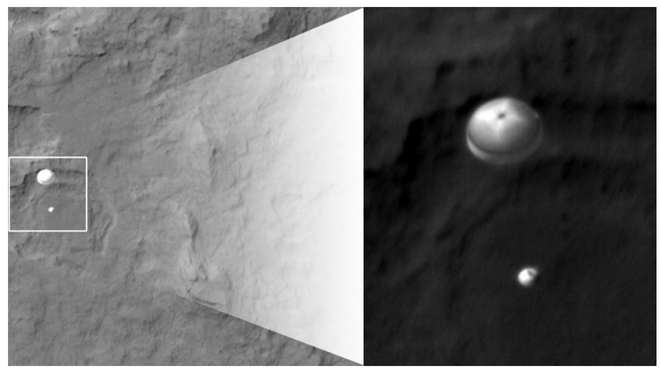


Figure 1: HiRISE image of the MSL DGB parachute in flight at Mars. Credit: NASA/JPL-Caltech/Univ. of Arizona

The first successful DGBs used at Mars on the Viking 1 and 2 landers were designed by leveraging data generated by the Planetary Entry Parachute Program (PEPP) and Supersonic Planetary Entry Decelerator (SPED) test programs [2]. Ultimately, a series of near flight-like, end-to-end tests of the Viking parachute system were executed in the Balloon Launch Decelerator Test (BLDT) series. These tests were performed at Mars relevant dynamic pressures and Mach numbers using a flight-scale forebody and canopy [3]. The PEPP, SPED, and BLDT results would provide engineers with sufficient data to design successful supersonic DGBs for use at Mars for the next 40 years. However, the complexity and resources required to repeatedly execute high altitude supersonic tests proved to be too high for most missions after Viking to undertake. As such, parachute deployment, inflation, and flight performance was systematically decomposed into chunks that could be more easily tested, analyzed, and qualified. This decomposition has been referred to as "the five pillars," and is described in Figure 2. The systematic approach described in Figure 2 was successfully used to demonstrate flight worthiness of the Mars Science Laboratory (MSL) parachute decelerator system.

Despite the successful run of the DGB, the Low-Density Supersonic Decelerators (LDSD) project endeavored to design and test a large supersonic ringsail parachute with greater performance than the DGB. To accomplish this task, the LDSD project set forth to perform a series of high altitude supersonic

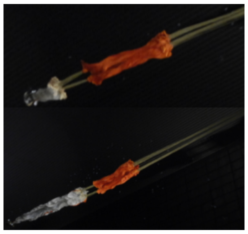
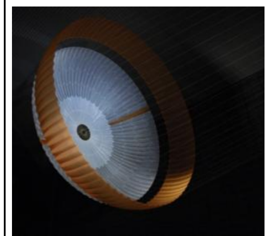
Phase 1: Mortar Deployment	***Phase 2: Canopy Inflation***	***Phase 3: Inflation Strength***	***Phase 4: Supersonic Performance***	***Phase 5: Subsonic Performance***
				
Parameters/Components of Interest • Deployment bag design • Line stretch mechanics • Packing methodology • Bag strip mechanics • Deployment bag retention	***Parameters/Components of Interest*** • Canopy inflation dynamics • Parachute design • Flow field	***Parameters/Components of Interest*** • Flight Limit Load on chute • Cyclic load on parachute to represent "area oscillation"	***Parameters/Components of Interest*** • Parachute configuration • Drag coefficients • Mach efficiency curve • Stability coefficients • Area oscillations	***Parameters/Components of Interest*** • Parachute configuration • Drag coefficients • Mach efficiency curve • Stability coefficients
Relevant Test Environment • Mortar ejection in low speed trailing flow (bounding) • Parachute/mortar design	***Relevant Test Environment*** • Mach number • Flow velocity & density • Parachute design	***Relevant Test Environment*** • Dynamic pressure • Parachute design	***Relevant Test Environment*** • Mach number • Flow velocity & density • Parachute design	***Relevant Test Environment*** • Flow velocity • Parachute design
Method of Qualification • Static mortar fire testing • Mortar ejection in the NFAC wind tunnel • Analysis to flight conditions	***Method of Qualification*** • Similarity to PEPP and BLDT high altitude supersonic parachute deployments • Flight experience of Viking, MPF, MER, and Phoenix	***Method of Qualification*** • Sea level subsonic testing in the NFAC wind tunnel	***Method of Qualification*** • Similarity to PEPP and BLDT high altitude supersonic parachute deployments • Flight data • CFD and subscale supersonic wind tunnel tests to verify similarity	***Method of Qualification*** • Sea level subsonic testing in the NFAC wind tunnel • Aerial drop testing and flight data from the Phoenix program

Figure 2: Five Pillar method by which the MSL parachute was qualified for flight.

tests using a full scale forebody and parachute canopy, similar to the BLDT architecture used in the Viking era. Leading up to each of these supersonic tests, the parachute system was tested and analyzed according to the five pillar methodology to maximize the chance of success of each test. LDSD performed two supersonic tests, one in 2015 [4] and one in 2016 [5], both of which resulted in canopy failures below the flight limit load (maximum parachute drag load at which the parachute is designed to safely operate). The LDSD anomalies launched an investigation into the five pillar methodology, particularly in the fundamental assumptions in the heritage analysis and test methods within Inflation Strength (third) pillar. This investigation lead to a greater understanding of the limitations of these methods, which consequently cast some uncertainty on parachute performance predictions for prior Mars missions, including MSL.

In addition to a more thoughtful look at the heritage assumptions within the third pillar, the historical DGB data set was analyzed to look more closely at how much structural margin has been historically present. Previous DGBs were all analyzed using a thin-wall pressure vessel methodology to determine their theoretical ultimate strength, which was compared to the loads at which they were actually flown [2]. This analysis illustrated how the structural margin (defined by the difference between the theoretical ultimate capability and the load at which it actually flew) present in the MSL canopy may have been lower than any previous canopy flown either at Earth or Mars. Although simplistic in nature, this analysis cast more uncertainty on the likelihood that the MSL parachute design could survive an inflation at its flight limit load of 65,000 lb.

The amalgamation of the factors stated above has caused the perceived risk of flying a heritage MSL build-to-print (BTP) parachute with a heritage structural verification program, to increase to an unacceptable level. As such, the Mars 2020 project has embarked on an extensive parachute development and test program to help reduce the risk of the parachute system back to an acceptable level. This program involves three separate tasks:

- Construct a heritage MSL BTP parachute assembly and, in parallel, design and fabricate a similar DGB parachute that uses stronger materials. The purpose of this new design would be to create an MSL-size DGB that has structural margins that are more in-family with previously successful DGBs at Mars and at Earth, but also maintain the parachute configuration that was successful at Mars during MSL.

- Perform lot workmanship verification testing on both the BTP and strengthened parachutes by performing mortar deployed inflations in a subsonic wind tunnel. The purpose of this test is to examine the fully inflated canopy under load to verify appropriate construction. Additionally, as mortar deployed inflations were a crucial part of the MSL parachute program, performance of this test for Mars 2020 provides a convenient sanity check that the new canopies at least satisfy the MSL criterion.

- Perform high altitude supersonic testing of the full-scale parachutes at Mars-relevant Mach numbers and dynamic pressures. The purpose of this test is to serve as the closest test-as-you-fly (TAYF) condition to enable the parachute to witness a fast, chaotic supersonic inflation at loads bounding the flight envelope at Mars. This test stems from the realization that heritage analysis and test methods provide relatively poor verification of the canopy stresses encountered during a supersonic inflation.

The purpose of this paper is to present the thought process and evidence behind why an extensive parachute test program is being pursued for Mars 2020 despite the successful operation of the MSL parachute and despite the build-to-print nature of the rest of the Mars 2020 entry, descent, and landing architecture. Construction of the two different parachute designs has already begun and the subsonic test program is complete. These items will be discussed below. The high altitude supersonic test program has recently completed its first launch, the details of which are discussed by O'Farrell et al. [6].

2. How Risk Changed Between MSL and Mars 2020

Perceived Risks during MSL

One of the primary perceived risks against the MSL parachute that needed to be mitigated prior to launch was that it would be a supersonic inflation of the largest supersonic DGB ever flown. The MSL parachute had a nominal diameter of 21.35 m, which was larger than any DGB flown supersonically at Earth or Mars. The next largest DGB to have been successfully flown supersonically at Earth was a 19.7 m nominal diameter DGB flown at Mach 1.59 in 1967 [7]. This DGB is shown in Figure 3, which inflated successfully, but suffered damage to the disk due to recontact from the deployment bag.

Figure 3: 19.7 m nominal diameter DGB successfully inflated, but suffered damage when the deployment bag recontacted, and penetrated through, the disk portion of the canopy. The deployment bag is seen to the left of the canopy and is moving towards the camera.

A supersonic test program was briefly considered, but test architectures considered at that time were found to be too resource intensive relative to other high risk needs across the flight system. Ultimately, the physics governing the supersonic inflation process of a 21.35 m nominal diameter DGB were determined to be not sufficiently different from those governing the supersonic inflation of a 19.7 m nominal diameter DGB. Thus, the Supersonic Inflation (second) pillar was satisfied via similarity to a historically successful DGB despite the 17% areal size difference between two chutes.

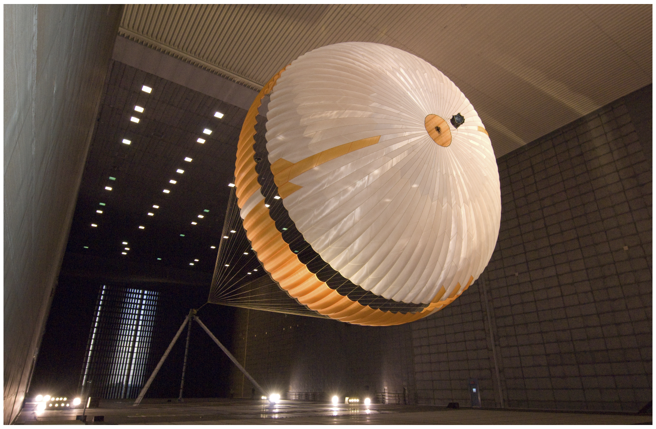
The Inflation Strength (third) pillar was satisfied via both analysis and test for MSL. Verification testing involved multiple mortar deployed inflations of the full scale parachute in the National Full Scale Aerodynamics (NFAC) subsonic wind tunnel at a load of 81,250 lb (1.25x the flight limit load of 65,000 lb). This subsonic overload testing was deemed sufficient to retire risks related to the inflation strength of the canopy for several reasons. First, supersonic inflations at Mars are referred to as infinite mass inflations, meaning that the vehicle experiences negligible dynamic pressure loss during the inflation process (as if the payload mass were infinite). Because the dynamic pressure is nearly constant during the inflation, peak load occurs at full inflation. The wind tunnel generates a similar infinite mass condition because it pulls a near constant dynamic pressure during the parachute inflation process and also causes peak inflation load to occur at full inflation. Second, the parachute is inflated via a mortar deployment in the wind tunnel, meaning that some of the inflation dynamics are captured during the test, albeit at a slower velocity with more damping due to the high-density flow surrounding the canopy. Third, it was assumed that peak stress in the canopy was correlated with the parachute load. Thus, peak stress in the canopy would occur at the peak load, which occurs at full inflation, shown in Figure 4a. Because it was (and currently still is) exceedingly difficult to perform an in-situ measurement of canopy stress during the inflation process, a quasi-static assumption that the peak stress at any part of the canopy increased monotonically with the parachute drag force was felt to be appropriate at the time of MSL.

Because it was believed that peak stress was related to the peak parachute load at full open, parachute analyses were performed with the canopy in its full open state. Using a legacy parachute analysis tool called CAnopy Loads Analysis (CALA) [8], a uniform pressure was applied to the canopy until the axial force generated by the canopy equaled the flight limit load. A representative CALA analysis result from MSL is shown in Figure 4b. This analysis produced estimates of stresses in the canopy, which were compared to joint strength test data to determine if there was sufficient margin between the tested capability of a given joint and the peak stress predicted in the canopy. For MSL, this analysis process showed positive margins, with a 1.5x factor of safety, against seam and joint ultimate capability. Satisfaction of these two pillars via analysis and test retired sufficient risk for MSL regarding the inflation of the largest supersonic DGB ever flown.

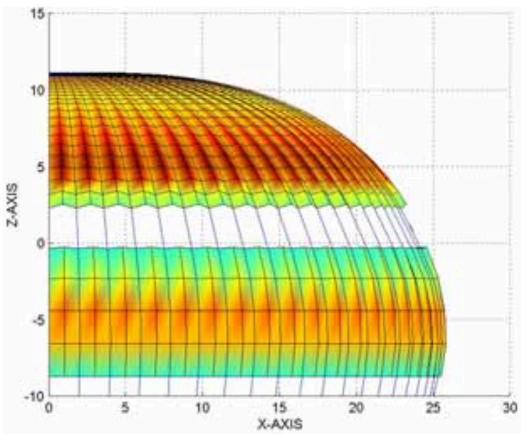
How LDSD Changed the Perception of Parachutes

The purpose of the LDSD project was to develop three new decelerator technologies for use in low-density atmospheres for the next generation of heavy landers at Mars. One of these technologies was a large, 30.5 m nominal diameter supersonic ringsail parachute [9]. These technologies were to be demonstrated at Mars-appropriate supersonic Mach numbers and Mars-appropriate atmospheric densities using an architecture similar to that used by the Viking program in the BLDT series [10]. Due to the complexity and expense of these full-scale high altitude tests, it was necessary to perform due diligence on the parachutes prior to each flight to minimize the risk to each flight. Given the successful implementation of the five pillar methodology on MSL, it was natural for LDSD to implement the same methodology to verify the parachute deployment, inflation, and performance prior to the supersonic flight tests.

The pillar of particular importance for this discussion is the Inflation Strength (third) pillar, which is intended to verify the capability of a parachute to survive a supersonic inflation at a load equal to, or less than, its flight limit load. The flight limit load is a requirement passed from flight dynamics



(a) MSL DGB parachute fully inflated in the NFAC wind tunnel. Image credit: NASA/JPL-Caltech



(b) Representative static analysis of the a fully inflated DGB parachute using CALA.

Figure 4: Activities performed to retire risks against the Supersonic Inflation and Inflation Strength pillars during the MSL parachute development program.

to the parachute system as the maximum parachute load experienced in statistically bounding flight conditions. All analyses and tests must demonstrate margin to this flight limit load, which was 80,000 lb for LDSD.

To verify inflation strength analytically, the LDSD parachute underwent a similar process as MSL, and in some ways was more rigorous than MSL. Because the LDSD parachute would also experience an infinite mass inflation and peak load would occur at full inflation, the parachute was analyzed in its fully inflated state subject to a uniform internal pressure distribution. However, instead of using CALA like MSL, a more modern tool was used that is called LS-DYNA. At the time of LDSD, LS-DYNA had become widely used in the parachute industry due to its higher fidelity material and physics models. Although there is no data that necessarily indicates that LS-DYNA generates more accurate results than CALA, it does have documented verification against thin-membrane problems similar to parachutes that help provide confidence in the models and solver [11]. Similar to MSL, analytical margins are calculated assuming a 1.5x factor of safety.

To verify inflation strength experimentally, LDSD invented a new method by which parachutes could be quasi-statically loaded. The LDSD parachute was too large to fit in the NFAC test section, where the MSL parachute was tested. As such, LDSD constructed an open-air infrastructure in which a parachute was deployed from below a helicopter and allowed to inflate. After inflation, the parachute riser would engage with a rocket sled, which would ignite and pull the parachute towards the ground, creating a high parachute load in its fully inflated state. This rocket sled parachute test architecture is shown in Figure 5 and is described in greater detail by Meacham et al. [12]. Rocket sled test results on the two LDSD parachutes are discussed below in context of the supersonic flight results.

Figure 5: Structural verification test of an LDSD ringsail parachute via rocket sled.

There were two LDSD flights, both of which resulted in canopy structural failures and total loss of the parachutes. Each flight taught an important lesson on the behavior of supersonic parachutes and the methods by which they were verified for flight. For the first supersonic flight dynamics test (SFDT), a “disksail” (a ringsail canopy with a flat solid circular disk in place of the ringslot portion of the canopy) was used and the parachute was analyzed at its flight limit load of 80,000 lb in its fully inflated state. This analysis showed positive margins across all elements of the canopy at the flight limit load. The lowest margin appeared in the joint between the suspension lines and the riser whereas margins in the canopy and reinforcements were at least 50%. Unfortunately, a rocket sled verification test of the disksail was not performed prior to the first supersonic flight of the disksail parachute due to schedule restrictions. However, a rocket sled test was performed on a disksail after the first supersonic test. In this test, the parachute experienced canopy damage in the form of a tear along a radial that extended from the skirt to the vent, which occurred at a load around 80,000 lb. In flight, the disksail began inflating but started failing in the disk portion very early, when the parachute was only generating approximately 9000 lb of force, as shown in Figure 6a. The canopy continued to tear and was totally lost. This failed parachute was the first test to illustrate an important aspect of supersonic parachutes – that showing positive structural margin using quasi-static analyses was insufficient to show that the structure can actually survive a supersonic inflation. It was clear from this test that the canopy developed stresses that exceeded the capability of the material very early in the inflation process, meaning that peak stress does not necessarily occur at full inflation. It appeared from the SFDT-1 result that asymmetry and dynamics can occur during the inflation process that can result in very high stresses while the canopy is in a partially inflated state. Additionally, it was clear from the post-flight rocket sled test that a subsonic failure of the canopy can manifest in a different way, and at a different load, than during a supersonic inflation.

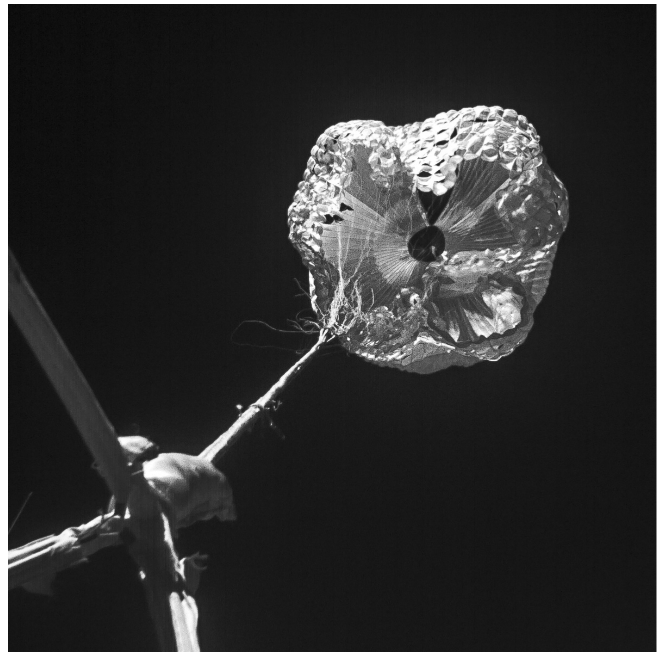
After the SFDT-1 parachute failure, the parachute was redesigned as a standard ringsail and the parachute was analyzed to a much higher load in an attempt to create a more bounding stress state in the canopy. Instead of being analyzed at 80,000 lb, the SFDT-2 ringsail was analyzed at 166,000 lb, which was a static load intended to represent the stress augmentations due to the dynamics and asymmetry observed in the SFDT-1 inflation. Even at this high load, the analysis still indicated positive margins with a 1.5x factor of safety on the material ultimate strength. Unlike SFDT-1, a parachute from this lot was subjected to the rocket sled structural verification test. During this test, the parachute survived to a load of approximately 120,000 lb and eventually failed at the suspension line-to-riser joint, which was the expected failure point. Leading into the SFDT-2 flight, there was confidence that the parachute had been analyzed and tested as well as possible. However, during the supersonic inflation of the SFDT-2 ringsail parachute, the parachute failed at just under the flight limit load, around 79,000 lb, as shown in Figure 6b. This failed parachute had two important ramifications for supersonic parachutes going forward. First, this failure indicated that quasi-static analyses of parachutes, even analyses that have been augmented by 200% to try to account for asymmetry and dynamics during a supersonic inflation, do not predict bounding stress conditions within the canopy. Second, performing a subsonic ground test of a parachute in its full open state at a load that is as high as 150% above the flight limit load does not provide evidence that the parachute will survive a supersonic inflation at the flight limit load.

In summary, LDSD had the following implications on heritage methods used to verify that a parachute could survive a supersonic inflation at, or below, its flight limit load:

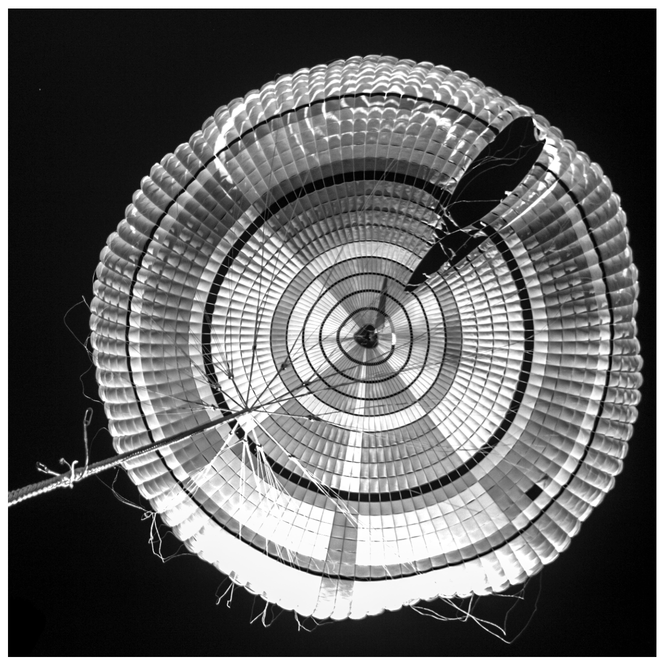
- It indicated that peak stress in the canopy does not necessarily correlate with peak load and indicates that drag force generated by the canopy may not be well correlated with canopy stress at all.

- It indicated that significantly higher stresses can be generated in the canopy than those predicted by quasi-static analyses of a full open canopy, even if the quasi-static load is amplified significantly to attempt to compensate for the additional dynamics and asymmetries that can occur during a supersonic inflation.

- It indicated that a subsonic overload test of the full open canopy does not provide sufficient evidence that the canopy will survive a supersonic inflation at, or below, the flight limit load.



(a) Failure of the SFDT-1 disksail parachute at a load of approximately 9000 lb.



(b) Failure of the SFDT-2 ringsail parachute at a load of approximately 79,000 lb.

Figure 6: Failures of the two LDSD 30.5 m nominal diameter supersonic parachutes.

It should be noted that the conclusions formed from LDSD are based entirely on experiences with ringsail-like parachutes, not the DGB parachutes that were typically used for all previous Mars missions. Because of this, it is possible that heritage analysis and test methods actually do hold for DGBs and simply do not hold for ringsail parachutes. However, there is not sufficient data to conclusively determine that the DGB is exempt from the lessons learned from LDSD, and in the face of the conclusions drawn from LDSD, it would be non-conservative to ignore these results and push forward with a heritage DGB verification program.

Retrospective Uncertainty

The three implications of the LDSD project described above fundamentally changed the viewpoint of the risks retired by these heritage activities in previous missions, such as MSL. The analyses presented at MSL design reviews, which showed positive margins for a parachute analyzed at the flight limit load of 65,000 lb, no longer provided confidence that the canopy could survive a supersonic inflation at 65,000 lb. Similarly, it challenged the evidence provided by a subsonic parachute overload test that the parachute could survive a supersonic inflation at its flight limit load. With doubt cast upon these two cornerstones of the Inflation Strength pillar for MSL, there remained one piece of data that was extremely valuable and irrefutable – that the MSL parachute successfully inflated at a Mach number of 1.70 at a peak load of 34,580 lb. This provides some confidence that a parachute built in the same way could survive a supersonic inflation at loads less than or equal to 34,580 lb. The question then became – how much risk does reuse of an MSL parachute design place on the project?

It is difficult to answer that question without performing a supersonic inflation test that results in canopy failure. But it may be possible examine the risk of the MSL parachute in terms of its similarity, or difference, to other previously successful supersonic DGBs. Clark and Tanner [2] interrogated the historical DGB data set in an attempt to normalize all DGBs to a single metric that accounted for parachute size and the strength of the materials they were made from. To accomplish this normalization, all DGBs were assumed to be thin-walled pressure vessels and their theoretical ultimate load capability was determined from the materials from which the parachutes were constructed. The residual margin in each parachute was computed by dividing this theoretical ultimate load by the load at which that particular parachute was actually deployed. Figure 7 shows the outcome of that work.

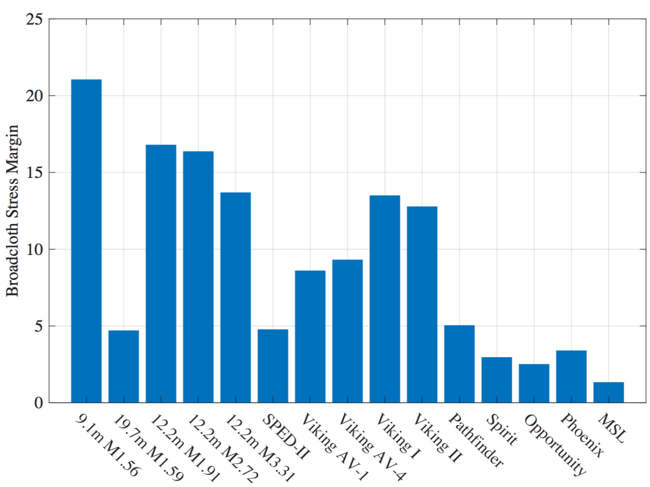


Figure 7: Parachute canopy margin for historical DGBs, where more margin indicates that a parachute was likely operating further from its ultimate capability.

The height of the bar effectively indicates how much margin was built into the parachute relative to the peak load it actually hit during its flight. A larger bar could be interpreted as less risk, as the parachute was operating further away from its ultimate capability. These data indicate that MSL likely took the most risk with regards to operating closest to its ultimate load relative to any other DGB flown at Earth or Mars. Although these data are not conclusive, it does provide some indication that flying at loads near the upper end of the loads dispersion at Mars (closer to the flight limit load) would be more risky than any previous Mars mission to date.

Perceived Risks on Mars 2020

Based on the information provided above, the risks to the Mars 2020 parachute system are explicitly stated below:

- It is possible for stresses to be higher mid-inflation than at full inflation, making analyses of a full open canopy non-conservative. Beyond that, there exists no data to anchor or validate any analysis method regarding the stresses developed in a parachute canopy. This renders the assessment of structural margins in the parachute canopy unreliable expect for on a comparative basis (i.e. comparing multiple designs as in Figure 7).

- Subsonic overload testing, either in the form of a subsonic inflation in a wind tunnel or a quasi-static force applied to a full open canopy, does not necessarily provide sufficient evidence that the parachute canopy will survive a supersonic inflation at its prescribed flight limit load. There are highly dynamic and chaotic events that occur in a short time span during a supersonic inflation, which cannot be mimicked or sufficiently bounded by subsonic testing.

- The MSL parachute operated at only 53% of its flight limit load at Mars. With the uncertainty cast upon the MSL analysis and test methods, there exists no data to indicate that the MSL canopy will survive a supersonic inflation above 34,580 lb with high confidence. On the contrary, a comparative analysis of historical DGBs appears to indicate that, even at 53% of its flight limit load, the MSL parachute may be operating less conservatively than all previously successful supersonic DGBs.

Due to these factors, the perceived risk of flying an MSL parachute on the Mars 2020 mission has increased above where it was for MSL, despite the fact that all perceived parachute risks at the time of MSL were reduced to an acceptable level and that the MSL parachute functioned successfully at Mars. The Mars 2020 project has initiated an extensive parachute development and test program to address these new risks and to once again reduce parachute risks to an acceptable level prior to launch in July 2020.

3. Plan to Mitigate Risk

The plan to mitigate the risks to the Mars 2020 parachute system involves three activities, described below. These activities involve construction of two parachute designs, workmanship testing of the canopy in a wind tunnel, and high altitude supersonic inflation testing.

Two Parachute Designs

The project is pursing the simultaneous development of two independent parachute systems. One parachute system is a BTP MSL heritage DGB, designed and fabricated by Pioneer Aerospace Corporation. Although there is uncertainty regarding the MSL parachute's capability at higher loads, there is not definitive evidence that it will not work at the Mars 2020 flight limit load, and the MSL parachute may still represent the lowest risk option because it already has demonstrated success at Mars. A second DGB parachute system is being designed and fabricated by Airborne Systems North America that is the same nominal diameter as the MSL DGB, but has been designed with materials that are stronger than the MSL design in key areas. This is hereto referred to as the strengthened parachute configuration. The two parachute

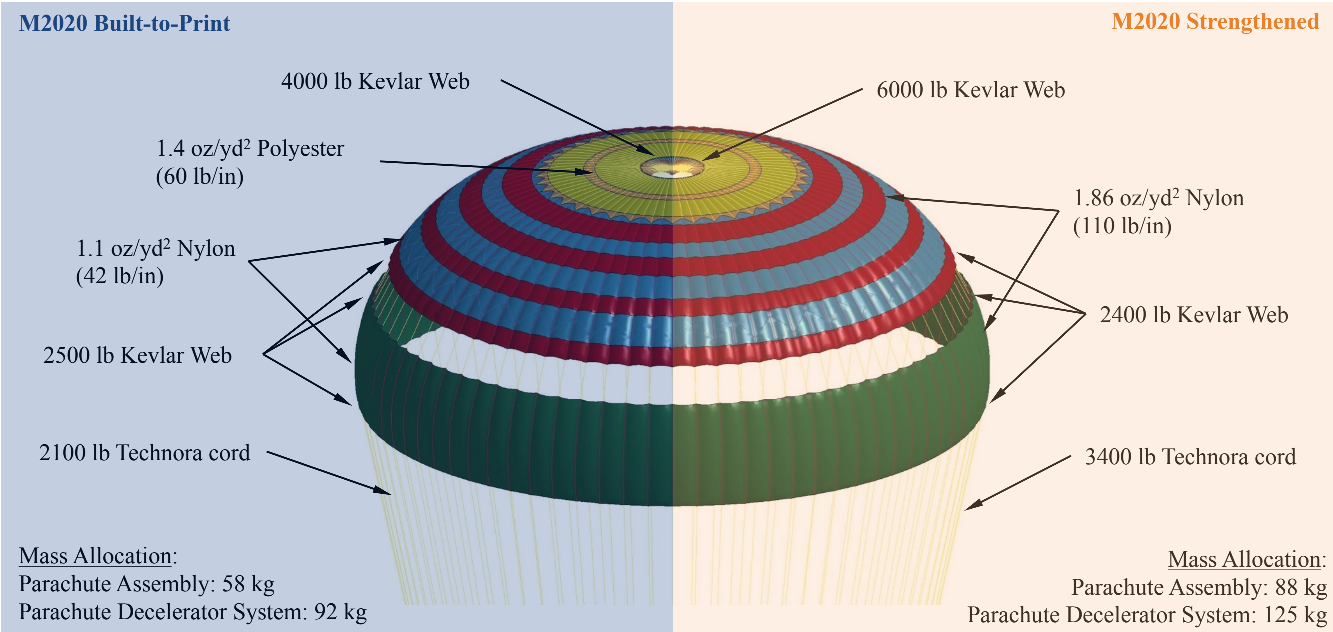


Figure 8: Comparison of the two DGB designs for Mars 2020.

designs are compared in Figure 8.

Once the parachute designs are frozen, several parachutes of each configuration will be fabricated as one lot of assemblies using all of the flight processes and requirements. This manufacturing philosophy ensures that all parachutes that are tested are as similar as possible to the flight units, maximizing the confidence of the parachute assembly that operates at Mars.

Subsonic Workmanship Testing

The parachutes are measured on the table following manufacturing to ensure that they meet drawing requirements, but there is no way to observe the fully inflated parachute to verify that it was constructed correctly other than a test. Although a subsonic wind tunnel may not provide an effective demonstration of inflation strength for supersonic parachutes, it does allow for close inspection and verification of manufacturing workmanship. The wind tunnel conditions can be controlled to ensure that a given load is obtained on the canopy and cameras can be positioned throughout the test section to photograph the canopy from all angles to examine the inflated shape and identify any concerning behavior in flight. Additionally, a subsonic workmanship test acts as risk reduction for the high altitude supersonic test, which is significantly more resource intensive than the wind tunnel test.

Workmanship testing occurs in the 80-ft by 120-ft test section at the National Full Scale Aerodynamics Complex (NFAC) at NASA Ames Research Center. Testing consists of mortar deployed inflations of both parachute designs and provides the first end-to-end test of the mortar ejection, orderly deployment after ejection, bag strip, and inflation, albeit at a slower time scale than the supersonic deployment. The test also stresses the parachute assembly to observe how the structure carries load and helps identify any abnormal high stress areas. The test conditions are identical to the mortar deployed inflation tests performed by MSL, which demonstrates that the Mars 2020 parachute assemblies perform at least as well as the MSL parachute in same the subsonic environment.

The parachutes are launched at tunnel centerline by mounting the mortar tube on a 2-degree of freedom launch arm. The launch arm, and subsequently the parachute loads, are supported by a tripod structure, shown in Figure 9. The test section is outfitted with 22 different cameras, as shown in Figure 10, to capture every portion of the deployment and inflation of the parachute canopy. Additionally, parachute load measurements and tunnel operating conditions were measured.

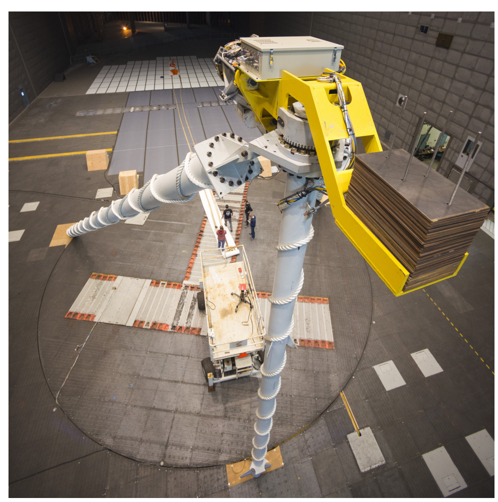


Figure 9: Tripod and launch arm supporting the parachute during wind tunnel testing.

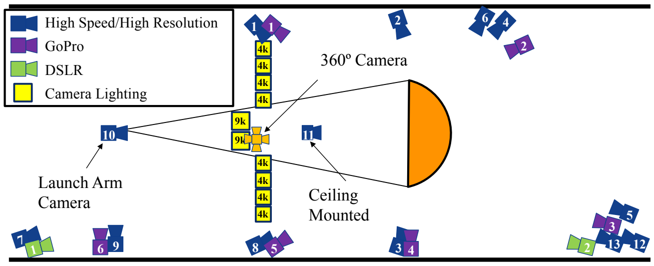


Figure 10: Camera layout to capture parachute deployment and inflation during wind tunnel testing.

High Altitude Supersonic Testing

The fundamental issue at the root of nearly all of the parachute risks for Mars 2020 is that a supersonic parachute inflation is dynamic and chaotic, to the point that analytical and ground test methods have not been shown to sufficiently replicate, or bound, the stress environment on the canopy. The only way to sufficiently retire these risks is to perform a supersonic test of the parachutes at Mars-appropriate Mach numbers, atmospheric densities, and parachute loads.

Leveraging lessons learned from the LDSD project, a test architecture called the Advanced Supersonic Parachute Inflation Research and Experiments (ASPIRE) was developed that could deliver a full scale Mars 2020 DGB parachute to appropriate Mars-like supersonic conditions at Earth. The parachute and mortar are installed into a 28.5" diameter payload section weighing approximately 1200 kg and launched using a Terrier-Black Brant IX sounding rocket, shown in Figure 11. The sounding rocket delivers the payload to altitudes between 38 and 47 km and Mach numbers between 1.6 and 2.1, at which point the parachute is deployed. The objective of this test focuses on the supersonic inflation of the parachute, not necessarily the parachute behavior and aerodynamics after inflation. The inflation portion is not thought to be as heavily influenced by the presence of a blunt forebody as the supersonic and subsonic aerodynamic performance after inflation. This permits the parachute to be deployed behind a slender body, which greatly simplified launch operations. The targeted parachute inflation loads are expected to range between 35,000 lb and 70,000 lb.

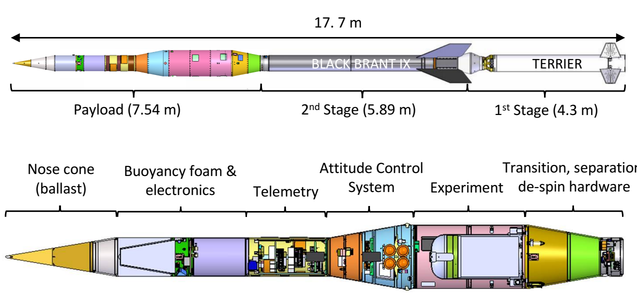


Figure 11: Diagram of the ASPIRE sounding rocket test architecture.

The payload section is outfitted with an instrumentation ring that includes three high-speed, high-resolution cameras operating at 1000 fps at approximately 4K resolution, three situational video cameras operating at 30 fps at 1080p resolution, and load pins to measure parachute and bridle loads. This instrumentation ring is shown in Figure 12.

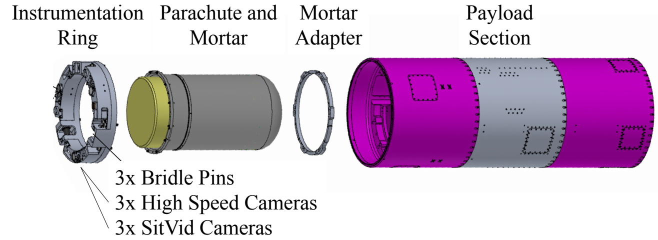


Figure 12: Exploded diagram of the parachute, mortar, instrumentation ring, and payload section.

The overall strategy is to perform at least three inflations for a given parachute design. The first test would perform a supersonic inflation at approximately 35,000 lb and a Mach number of approximately 1.7 in order to replicate the MSL deployment condition at Mars. This purpose of this test is to verify functionality of the test architecture as well as verify that the parachute has inflation strength at least equivalent to MSL. Next, the flight would target an inflation load of approximately 70,000 lb to demonstrate margin above the Mars 2020 flight limit load of 50,000 lb. The third flight would repeat the targeted 70,000 lb inflation load in an effort to quantify the flight-to-flight variability in the inflation dynamics. It is recognized that a sample size of two does not denote a statistically significant sample size. Because the supersonic inflation process is quite chaotic, it would be ideal to have tens of flights in order to begin to understand the variability in loads, shape evolution, and inflation dynamics associated with supersonic inflations. However, this sort of extensive test program would require resources beyond what is feasible for the Mars 2020 project and one repeat test was the best compromise for the resources required.

Down-Selection

Following all risk reduction activities, a down selection will occur in which one of the two parachute designs will be selected for flight at Mars. This down selection process will utilize all data collected on each configuration to assess which configuration represents the minimum risk to the flight system. The risk reduction plan outlined in this paper was initiated in 2016 with down-selection nominally planned to occur in 2018.

4. Preliminary Subsonic Test Results

The wind tunnel workmanship test of the Mars 2020 parachute systems occurred in June 2017. A BTP and strengthened parachute assembly each underwent a single mortar deployed inflation. Muzzle velocity of each deployment was captured using high speed photography of the ejection, shown in Figure 13.

The MSL heritage BTP parachute was ejected at a velocity of 44.5 m/s and a freestream dynamic pressure of approximately 775 Pa. The riser, suspension lines, and canopy all deployed in an orderly fashion from the deployment bag as it traveled down the test section. After line stretch, the parachute inflation took approximately 3.3 seconds to reach a peak load of approximately 76,300 lb at full inflation. The fully inflated BTP parachute is shown in Figure 14a. Post-test inspection of the BTP parachute assembly indicated no major damage to the canopy or any components.

The strengthened parachute was ejected at a velocity 44.3 m/s

Figure 13: Mortar fire of a parachute pack in the NFAC wind tunnel.

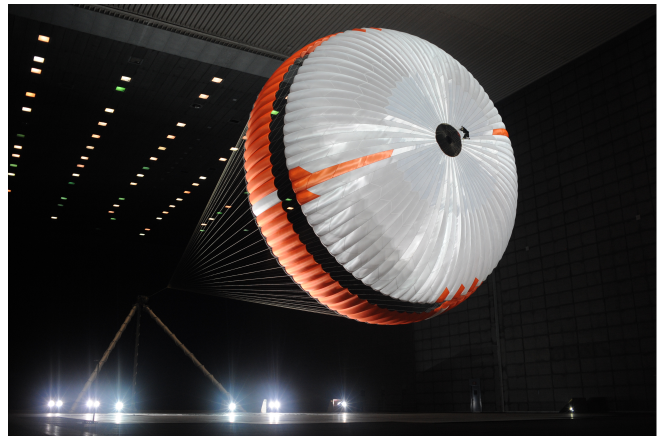
and a freestream dynamic pressure of approximately 780 Pa. The riser, suspension lines, and canopy all deployed in an orderly fashion from the deployment bag as it traveled down the test section. After line stretch, the parachute inflation took approximately 3.0 seconds to reach a peak load of approximately 90,700 lb at full inflation. The fully inflated strengthened parachute is shown in Figure 14b. Post-test inspection of the strengthened parachute assembly indicated no damage to the canopy or any components, although some of the stitches were popped along the single row of stitching between the radial cord and the broadcloth. These popped stitches did not compromise the integrity of the main seam, but did indicate a strain differential between the broadcloth and the radial.

Overall, both parachutes exhibited no indications of inadequate workmanship at peak loads that were at least 1.5 times higher that the highest peak inflation load expected at Mars for Mars 2020.

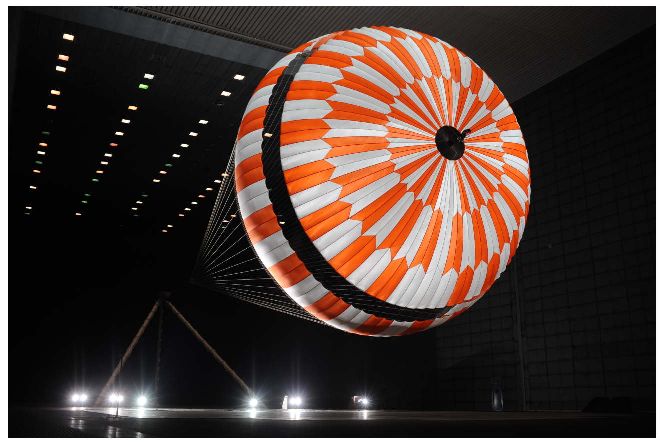
One peculiarity of this wind tunnel test is that the strengthened parachute generated a peak load that was approximately 14,000 lb higher than the BTP parachute. There were small differences that would drive the strengthened canopy to have slightly higher drag than the BTP, such as:

- The strengthened parachute had a nominal diameter of 21.51 m whereas the BTP had a nominal diameter of 21.38 m. This is equivalent to a 1.2% difference in the surface area.
- The strengthened parachute had a geometric porosity of 12.7% whereas the BTP had a geometric porosity of 21.85%.
- The strengthened parachute broadcloth material had a mean air permeability of approximately 80 cfm (measured at a pressure of 0.5 inches of water) whereas the BTP parachute broadcloth material had a mean air permeability of approximately 100 cfm.

However, the differences in these parameters are relatively small and would not immediately appear to cause such a difference in peak load between the two canopies. At present, the rather large difference in peak load remains unexplained, but will be scrutinized and analyzed further in the subsequent supersonic test program.



(a) MSL heritage BTP parachute.



(b) Strengthened parachute.

Figure 14: The BTP and strengthened parachutes flying in the NFAC wind tunnel after mortar deployed inflation.

5. Preliminary Supersonic Testing Results

The first supersonic flight test of a Mars 2020 DGB parachute occurred on October 4, 2017. This test was intended to serve as a shakeout flight of the mechanical hardware, flight system, operations, and payload recovery. Additionally, it was intended to verify that the ASPIRE test platform generated appropriate flight-like conditions for the parachute inflation. The ASPIRE test platform has several TAYF exceptions, including a faster inflation at Earth than at Mars for an equivalent Mach number deployment and dynamic pressure, a lighter weight vehicle that will lead to higher deceleration upon parachute inflation, and a slender vehicle that is generating a smaller wake relative to a blunt body. To verify that these TAYF exceptions did not invalidate the test, the first flight was outfitted with an MSL heritage BTP parachute and the deployment condition was targeted to achieve a peak inflation load of approximately 35,000 lb. This parachute configuration and deployment condition was as close to the successful MSL flight as possible, such that a successful inflation would indicate that the effects of the TAYF exceptions were small and that the test was valid.

The launch of the sounding rocket, shown in Figure 15, and payload separation occurred nominally. Mortar fire occurred approximately 57 seconds after payload separation, which ejected the parachute at 45.7 m/s and simultaneously accelerated the payload by 2.8 m/s, resulting in a total ΔV between the pack and payload of 48.5 m/s. After an orderly deployment of the riser and suspension lines, the parachute inflated successfully in 0.506 seconds, which was about 20% faster than the MSL parachute inflation at Mars. The fully inflated parachute is shown in Figure 16.

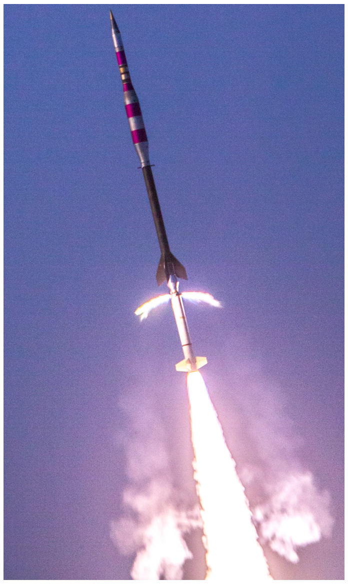


Figure 15: Launch of the first supersonic sounding rocket carrying an MSL BTP parachute. Image credit: NASA/WFF.

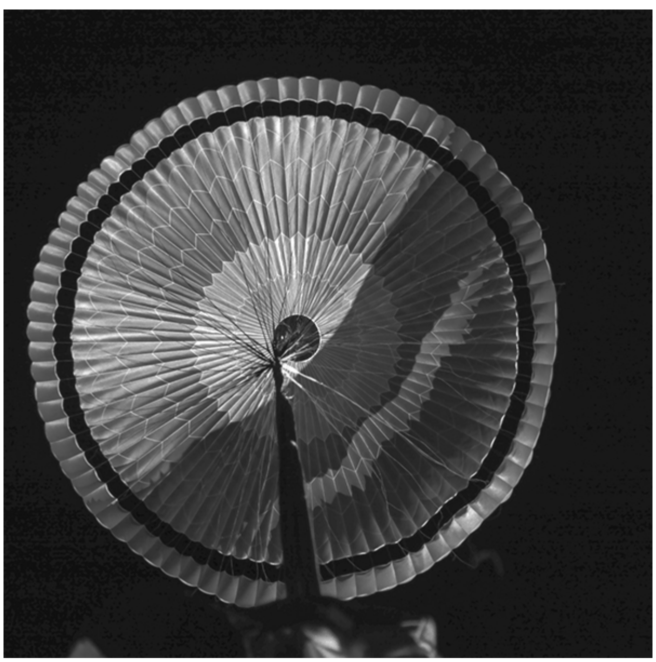


Figure 16: Full inflation of the MSL BTP parachute at a Mach number of approximately 1.7.

The parachute was quickly recovered out of the Atlantic Ocean after splashdown, shown in Figure 17. Subsequent inspection of the parachute assembly after recovery indicated some signs of high stress in the crown of the canopy and some areas along the suspension lines where yarns appeared to have been pulled or snagged out of the braid, although no yarns were broken. It is difficult to determine if these features occurred during the inflation process or occurred later during descent or recovery, but overall the parachute assembly was found to be in very good condition after the flight.

Figure 17: Parachute canopy sailing on the Atlantic Ocean just prior to recovery.

Additional details regarding the flight trajectory reconstruction, vehicle configuration, instrumentation, and parachute under test are provided by O'Farrell et al. [6].

6. SUMMARY

The largest ever supersonic DGB parachute operated successfully at Mars and helped safely land the Curiosity rover in 2012. However, since that time, experiences on the Low-Density Supersonic Decelerator project have indicated that heritage test and analysis methods used during the MSL project may be insufficient to verify the parachute's ability to withstand a supersonic inflation at its flight limit load. Additionally, a historical review of all successful DGB flights indicates that the MSL parachute may be out-of-family with regards to the conservatism in its construction. These revelations have called to question the reliability of reusing a heritage MSL parachute for the Mars 2020 mission, which may witness inflation loads higher than those measured on MSL. To help reduce the newly perceived risks on the Mars 2020 parachute system, the project has initiated a risk reduction plan that includes fabrication of two DGB parachute designs, a subsonic workmanship test program, and a high altitude supersonic test program. Both a BTP MSL parachute design and a strengthened parachute design will be subjected to workmanship and high altitude supersonic testing in order to collect data on their performance. The subsonic test program has already been successfully completed and the supersonic test program is underway. After conclusion of the supersonic test program, the residual risks of each parachute design will be assessed using the data acquired throughout the risk reduction program to down select to a single parachute design to fly to Mars in 2020.

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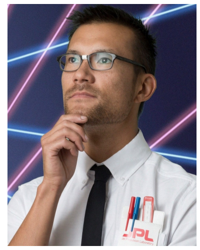
BIOGRAPHY



Christopher Tanner *is a Mechanical Engineer in the Entry, Descent, and Landing and Formulation group at the Jet Propulsion Laboratory. He has worked on the Low-Density Supersonic Decelerators project and currently is the cognizant engineer for the Mars 2020 parachute decelerator system. He holds B.S., M.S., and Ph.D. degrees in Aerospace Engineering from the Georgia Institute of Technology.*

Ian Clark *is a Systems Engineer at NASA's Jet Propulsion Laboratory, a specialist in the area of Planetary Entry, Descent, and Landing (EDL), and is the Principal Investigator of NASA's Low-Density Supersonic Decelerator (LDSD) Project. Dr. Clark is the recipient of a number of awards including the Presidential Early Career Award for Scientists and Engineers, the JPL Lew Allen Award, and the JPL Explorer Award. He holds B.S., M.S., and Ph.D. degrees in Aerospace Engineering from the Georgia Institute of Technology, where he also previously served as a Visiting Assistant Professor and managed the EDL research group.*

Allen Chen *is a systems engineer in the Entry, Descent, and Landing Systems and Advanced Technologies group at the Jet Propulsion Laboratory. He is currently the EDL Phase Lead for the Mars 2020 project. Prior to that, he spent a really long time working on the Mars Science Laboratory mission. He holds S.B. and S.M. degrees in Aeronautics and Astronautics from the Massachusetts Institute of Technology and a M.B.A. from the University of California, Los Angeles.*